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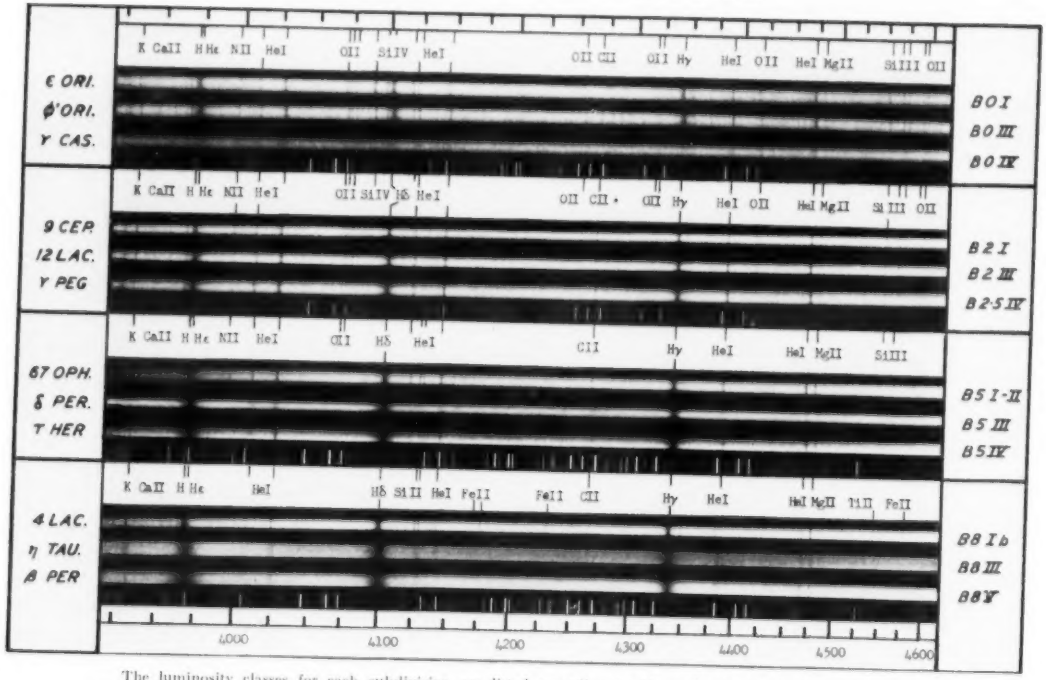
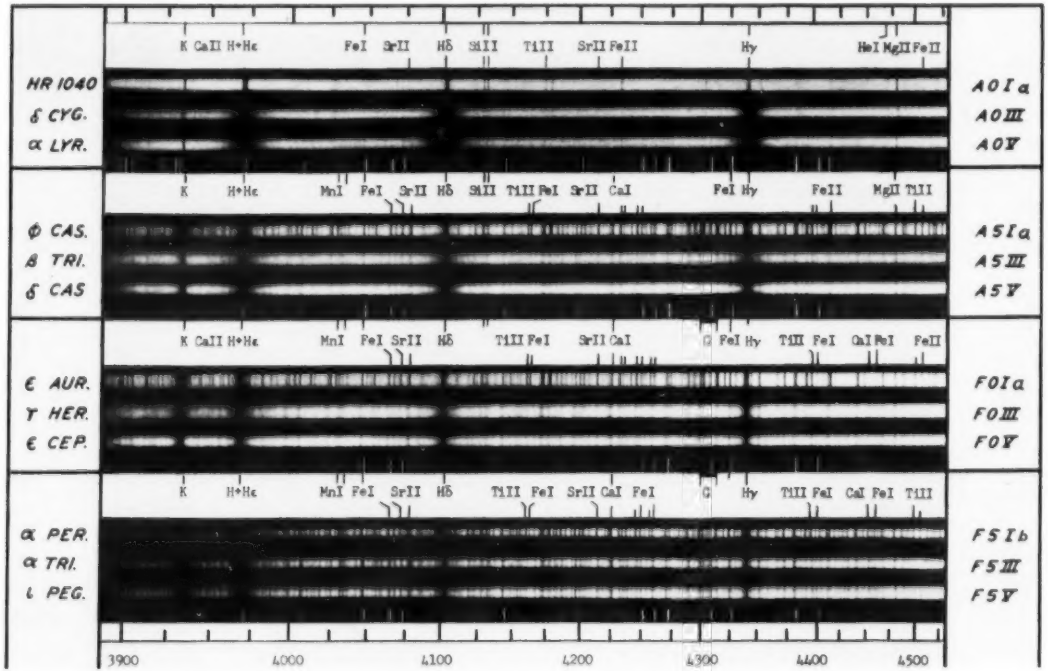
PLATE III—TYPICAL STELLAR SPECTRA OF CLASS B



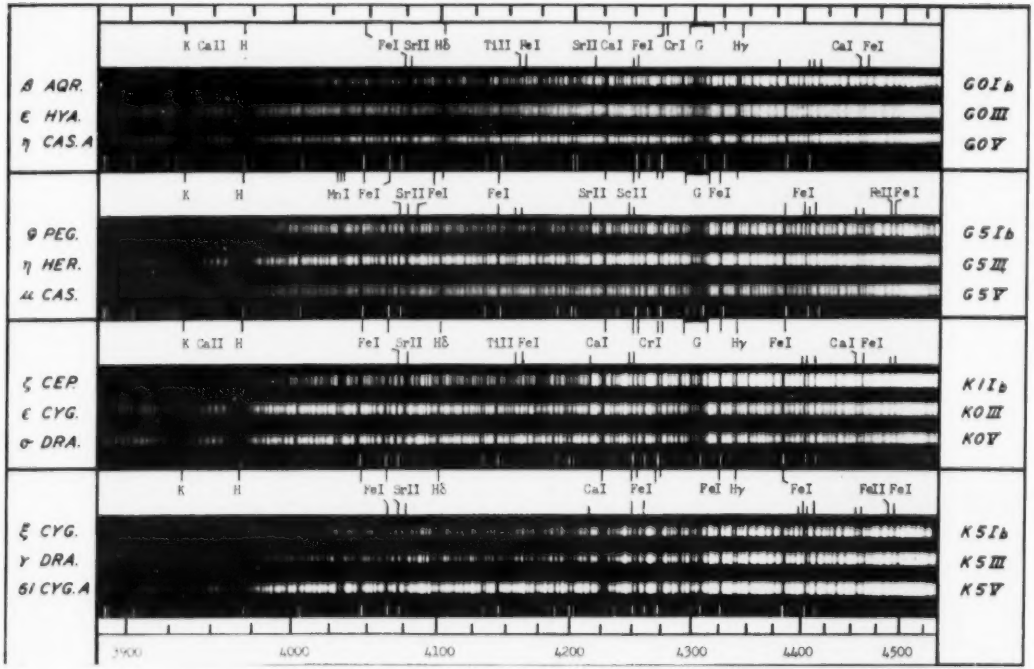
The luminosity classes for each subdivision are listed according to Morgan's classification, supergiant (I), giant (III), and main sequence (V). In the space above the spectra of each subdivision, the vertical strokes above the identifications represent lines suitable for determining the spectral type; those below the identifications are used for determining the luminosity class.

PLATE IV—TYPICAL STELLAR SPECTRA OF CLASSES A AND F



The luminosity classes for each subdivision are listed according to Morgan's classification, supergiant (I), giant (III), and main sequence (V). In the space above the spectra of each subdivision, the vertical strokes above the identifications represent lines suitable for determining the spectral type; those below the identifications are used for determining the luminosity class.

PLATE V—TYPICAL STELLAR SPECTRA OF CLASSES G AND K



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NOTES ON THE CLASSIFICATION OF STELLAR SPECTRA

(A Description of Plates III to V)

By K. O. WRIGHT

THE stellar spectra shown in Plates III to V were obtained with the one-prism spectrograph and long camera attached to the 72-inch telescope of the Dominion Astrophysical Observatory; the original dispersion was 22 A./mm. at Hγ and the slit-width was 0.05 mm. The stars were selected from the list of standards given in the Yerkes *Atlas of Stellar Spectra*[1] and thus may be considered to represent that system. Spectra of broad-lined stars were included only when stars having sharp lines were not available at the time of observation; the former indicate that such stars occur among early O-, B-, A- and early F-type spectra. The classification in the Yerkes *Atlas* includes stars from O5 to M2 with luminosity classes from I (supergiant) to V (main sequence or dwarf) with the exception that no luminosity classes are given for the early O-type stars and the dwarf M stars are not included. This system is the outgrowth of many others, particularly those of the Harvard Henry Draper catalogue and the Mount Wilson spectroscopic absolute magnitude programme. No doubt further revision will be effected in the future but the changes will probably be relatively small. These spectra are presented for comparison with

the Yerkes *Atlas*, which was assembled from low-dispersion spectrograms, in order to show their appearance under moderate dispersion.

The three plates depict spectra of classes B, A to F and G to K and show spectra of three luminosity classes for the various types. The wave-length scale is drawn at the top and bottom of each plate and for each section are shown the identifications of important lines, spectra of luminosity classes I, III, and V where possible, and an iron arc comparison spectrum taken from the same plates. The lines used for the spectral classification of each type are indicated by vertical lines drawn *above* the identifications; the spectral features used for determining the luminosity classes are indicated by lines drawn *below* the identifications. As is well known, the principal features used in the determination of spectral type were observed in the spectra of normal giants and main sequence stars; the spectra of supergiant stars are quite different and, in many cases, separate criteria must be used for their classification.

Since the criteria for spectral classification depend in part on the dispersion employed and since no discussion of the subject has appeared in this JOURNAL for many years, the following description may be of interest. It is based largely on the Report of the Classification of Stellar Spectra presented to the 1935 session of the International Astronomical Union,[2] on the Yerkes *Atlas*[1] and, for types F to K, on the luminosity criteria adopted at Mount Wilson[3] and Victoria.[4]

In the B stars, the range in effective temperature is from about 25,000°K to 11,000°K, which is considerably greater than in the later types, and therefore there is a correspondingly wide range in conditions of excitation. The O-type stars, which are even hotter, show strong HeII lines (λλ4200, 4542 and the Pickering series which is blended with the Balmer series of hydrogen) in the early types; these lines decrease in strength and are very weak at B0. The HeI lines (λλ4009, 4026, 4144, 4388 and 4471) and SiIV (λλ4089 and 4116) are weak in the O-type stars but become quite strong at B0.

At B0 the hydrogen lines (Hϵ, 3970; Hδ, 4102; and Hγ, 4340) are becoming stronger and, according to eye estimates, are about one-third their strength at A0. The OII lines (λλ4070, 4072, 4076, 4349, 4351, 4415, 4417, 4591, and 4596) are clearly seen;

and the SiIV lines are at their maximum. The luminosities of the stars are estimated by the ratios of intensity of the following lines: 4009, HeI: 4089, SiIV; 4072, OII: 4089, SiIV; and 4119, OII: 4144, HeI, all of which decrease with increasing luminosity. The NIII line at λ4097 is clearly seen here; when visible it indicates that the spectrum is very close to B0.

At B2 the HeI lines reach almost their maximum intensity; SiIV lines are now very faint and the OII lines are much weaker than at B0. SiIII lines reach their maximum at B1 and are decreasing in strength at B2. SiII lines at λλ4128 and 4131 are just appearing in these spectra. CII, 4267 is quite prominent and MgII, 4481, while becoming stronger, is weaker than HeI, 4471. The luminosity is determined from the intensity ratios 4009, HeI: 3995, NII; 4119-21, OII, HeI: 4144, HeI; and 4388, HeI: 4553, SiIII, NII, and from the wings of the hydrogen lines, Hδ and Hγ, which are less extensive in the giants.

At B5 the lines of CaII (K, 3934 and H, 3968) and MgII (4481) are becoming increasingly prominent; the sharp K and H lines visible in earlier types are almost entirely interstellar in origin, the ratio 4481, MgII : 4471, HeI is about 0.7, except in the supergiants. The SiII lines, λλ4128 and 4131 are stronger than at B2 and are intermediate in intensity between the HeI lines λλ4121 and 4144. CII, 4267 is still strong, the HeI lines are becoming weaker and the OII lines have almost disappeared. The luminosity is determined from the extent of the wings of the hydrogen lines as at B2.

At B8, MgII, 4481 is the same strength as HeI, 4471 for giant and main sequence stars, but CaII (K) is weaker than HeI, 4026. The HeI lines are still present but are much weaker, as also is CII. One of the best classification criteria is the ratio 4128-31, SiII : 4144, HeI, which is about 2 : 1. Many lines of the ionized metals, especially FeII, λλ4178, 4233, 4300, 4352, 4385, 4508, 4522, 4549, and 4583, appear in the supergiants which are also characterized by the lack of wings of the hydrogen lines.

Class A0 has always been considered an important point in the spectral sequence, for here the hydrogen lines reach their maximum strength. CaII (K) is increasing in intensity but is only about one-tenth as strong as Hδ; MgII, 4481 is also strong; SiII, 4128-31 is weaker than these lines but is near its maximum in this class.

On spectra taken with low dispersion or of stars with broad lines, the A0 spectrum appears very simple for the helium lines have disappeared and the metallic lines have not appeared, except in the supergiants. However with high dispersion both helium and metallic lines show faintly. The latter include FeI, 4046; FeII, 4233, 4508; TiII, 4501; CrII, 4558; and SrII, 4078, 4516. In supergiants numerous other lines of ionized metals also appear. The decrease in intensity of the hydrogen lines with increase in intrinsic brightness is the principal luminosity criterion.

At A5 the hydrogen lines are becoming less intense while CaII (K) is increasing in strength and is now stronger than Hδ. The MnI lines, $\lambda\lambda$4030-34 can now be seen and in the Yerkes *Atlas* the ratio 4030-34, MnI: 4128-31, SiII is the principal classification criterion. Many FeI lines can now be seen and are readily identified by their coincidence with the iron arc comparison lines. The *Atlas* luminosity criteria are the ratios of 4417, FeII to 4300, TiII, FeI, and to 4481, MgII. The difficulty in the classification of the supergiants is shown in the spectrum of φ Cas: on the Harvard Henry Draper system it is F5, on the Yerkes Atlas system it is A5 as shown here.

At F0 the hydrogen lines are only about one-half as intense as at A0. The CaII (K) line is nearly equal to CaII (H) + Hϵ and is about three times the intensity of Hδ; (in the present description the intensities are always eye estimates). The appearance of the G band, 4290-4315 and the ratio of 4227, CaI to 4340, Hλ are also used for classification by the Mount Wilson observers. The *Atlas* classification criterion is the ratio 4030-34, MnI: 4128-31, which is increasing with later spectral type; the luminosity criteria are the ratios 4172, TiII, FeI to 4132, FeI and to 4227, CaI.

By class F5 the lines of metallic atoms, both neutral and ionized, have become very prominent and only the best of the many numerous criteria can be indicated on the plates. At both Mount Wilson and Victoria it was found that there were a few line intensity ratios which could be used for determinations of absolute magnitude throughout the remainder of the spectral sequence. The component lines sometimes changed with type but the ratios remained a good indication of absolute magnitude. These ratios have been noted on the plates, in some cases without identification, and include 4071, FeI; 4078, SrII; 4162, TiII, SrII: 4168, FeI; 4216,

SrII: 4251, FeI; 4247, ScII: 4251, FeI; 4258, FeI: 4260, FeI; 4272, FeI: 4290, TiII, FeI ; 4400, TiII, ScII: 4405, FeI; 4455, CaI, MnI: 4462, FeI, VI, and 4489, FeII, FeI: 4495, FeI.

At F5, on the Harvard system the hydrogen lines are twice as strong as in the solar spectrum, 4227 CaI is about one-half the intensity of Hγ and the G band, 4290-4315 is becoming prominent. On the spectra in the Yerkes *Atlas*, 4046 FeI is weaker than Hδ and 4227 CaI, is weaker than Hγ; the violet side of the G band is stronger than the red. Luminosities are determined from the relative intensity of 4078, SrII and 4046, FeI, 4063, FeI, and also 4227, CaI.

At G0 the principal classification criteria are: Hδ is equal to 4227, CaI; Hγ is one and one-half times as intense as 4325, FeI; CaII (K) and (H) are increasing in strength; and the G band is well defined. The CrI lines at λλ4254 and 4274 are also becoming prominent. The luminosity criteria include those noted at F5 and also the ratios 4078, SrII to Hδ and to 4144, FeI.

At G5, Hγ is weaker than 4325, FeI; 4254 and 4274, CrI are increasing in strength, as also is 4227, CaI. The ratios used in the Yerkes *Atlas* are Hδ to 4144, FeI and to 4096, FeI and 4030-34, MnI,: 4300, the violet side of the G band, which latter is most prominent at this class. The luminosity is given by 4078, SrII to 4063, FeI, 4085, FeI, 4144, FeI, and 4227, CaI; 4216, SrII : 4251, FeI and the marked CN absorption to the violet of λ4215.

At K0 the Harvard criteria are: Hγ is twice as strong as 4325, FeI; 4227, CaI is three times its intensity in the sun and twice as strong as 4325, FeI; CaII (K) is at its maximum strength; and the G band is stronger than 4227, CaI. The Yerkes *Atlas* criteria are the blended ratios 4030-34, MnI : 4300, the blends 4290 : 4300 and 4096 : Hδ. The luminosity criteria are similar to those at G5.

At K5 the most conspicuous lines are CaII (K and H) and 4227, CaI; the latter is still increasing in strength since it is a neutral resonance line, as are the CrI lines λλ4254 and 4274; the FeI lines, including λ4046 and λ4383, are also becoming stronger. The G band is no longer an almost continuous absorption for the component lines can be distinguished easily. The *Atlas* criteria include the ratios 4227, CaI : 4325, FeI; the blends 4290 : 4297 and 4383, FeI : 4406 for classification and 4063, FeI : 4078, SrII, and 4216, SrII : 4260, FeI for luminosity.

It is to be noted that as the spectral sequence progresses from O to M the violet end of the spectrum becomes progressively weaker—in part due to the lower temperatures since the intensity maximum moves toward the red but probably also due to other general and molecular absorptions in the stellar atmosphere. The giants show this weakening more than the dwarfs and this could also be considered a general luminosity criterion.

At the present time one important field in stellar spectroscopy is the detailed analysis of a few stellar spectra in order to obtain information concerning these stellar atmospheres. This can be done either by comparing the observed intensities of spectral lines of different ionization and excitation and thus deducing the conditions of pressure, temperature and chemical abundance, or by computing models of possible stellar atmospheres, calculating the strengths of important lines and finding steliar spectra which fit these models. However for many problems involving stellar structure it is important that accurate spectral types and luminosities be known. As it becomes necessary to use lower and lower dispersion because the stars being studied are fainter, the large-scale features of the stellar spectra, which are given in the Yerkes Atlas, become important. Nevertheless it is still important to bear in mind and to use, when possible, the criteria of spectral type and luminosity applicable to spectrograms of moderate and high dispersion in order to utilize to the fullest extent the many advantages offered by greater resolution.

Dominion Astrophysical Observatory,
Victoria, B.C.,
November 1949.

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[2]Trans. Int. A. Un. 5, 180, 1935.

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Number 24

A THEORETICAL HERTZSPRUNG-RUSSELL DIAGRAM FOR RED DWARF STARS*†

By J. B. Oke

ABSTRACT

A series of stellar models for main sequence stars of small masses is studied in conjunction with two possible sources of energy, the carbon cycle and the proton-proton reaction. Hertzsprung-Russell diagrams are obtained assuming the two sources of energy separately. These are compared with observational data. It is found that the main sequence should have a considerable width if moderate variations in the chemical compositions of stars are present. The conclusions are that the carbon cycle models fit the observed data best. The proton-proton reaction models do not fit as well, but do give a solution for the hydrogen and helium content of the sun in good agreement with spectroscopic evidence.

Introduction. The best model which has yet been suggested for main sequence stars of small masses is one first devised by T. G. Cowling[1] in which a radiative envelope is fitted to a convective core of polytropic index 3/2. The equations of equilibrium of a star constructed in this way can be integrated by using a wide variety of assumptions. But for red dwarfs, the following assumptions are usually made.

(1) The chemical composition and the mean molecular weight are constant throughout the star. The star is assumed to be made up of hydrogen, helium, and Russell mixture, the fractions of each by weight being respectively X, Y, and $1-X-Y$.

(2) The perfect gas law is valid throughout the star.

(3) The radiation pressure is negligible compared with the gas pressure.

†This work was aided by the grant of a scholarship from the National Research Council of Canada.

*Summarized from a thesis submitted in partial fulfilment of the requirements for the degree of Master of Arts in the Department of Astronomy, University of Toronto, May, 1950.

(4) No energy is generated outside of the core of the star.

One postulate must be made concerning the opacity κ in the star. It is assumed to be represented by a generalization of Kramers' law, that is,

$$\kappa = \frac{\kappa_0}{\tau} \rho T^{-3.5} \tag{1}$$

where ρ is the density, T is the absolute temperature, and κ_0 is a function of X and Y. τ is the correction to Kramers' law and is termed the guillotine factor. Also it is assumed that $\tau = \tau_0 \rho^{\alpha}$ where it is convenient to write $\tau_0 = C_0(1 + X)^{\alpha}$. C_0 is an adjustable constant and α is a constant. For this representation of τ,

$$\log \tau = \log C_0 + \alpha \log \rho (1 + X). \tag{2}$$

A plot of $\log \tau$ against $\log \rho (1 + X)$ gives a straight line of slope α in which $\log \tau = \log C_0$ when $\log \rho (1 + X) = 0$. Such a plot will be referred to as a guillotine factor curve. With this form of the guillotine factor τ, homology-invariant models may be used which can be applied to stars of arbitrary mass M, luminosity L, radius R, and chemical composition X and Y. Each value of α employed denotes a different model and hence reference to a value of α specifies a certain model.

Cowling[1] integrated the first model of this type assuming the guillotine factor to be constant, i.e., $\alpha = 0$. M. Schwarzschild[2] performed the integrations for $\alpha = 0.25$. R. E. Williamson and G. F. D. Duff[3] have generalized the theory for arbitrary values of α and have carried out the integrations for $\alpha = 0.375$, 0.500, 0.550, 0.600, and 0.625. The integrations just mentioned lead to the equation,

$$\log \frac{LR^{0.5+3\alpha}}{M^{5.5+\alpha}} = 5.0937 + \log C_0 + \log C - 0.3276\alpha - (1 - \alpha) \log (1 + X) - \log (1 - X - Y) + 7.5 \log \mu \tag{3}$$

where we shall take

$$\frac{1}{\mu} = \frac{1}{2} + \frac{3}{2} X + \frac{1}{4} Y .$$

L, M, and R are in solar units, and all logarithms are to the base ten; this will be understood to be the case throughout this paper. C is of the nature of an eigenvalue of the differential equations of the model and is specified completely for each model. The determination of C_0 will be discussed later. Equation (3) gives one

relationship among L, M, R, X, and Y. A second relationship can be obtained by considering the energy production in the core of the star. The energy production per gram is taken as proportional to ρT^{ν} where ν is a constant.

For energy generation by the carbon cycle, $\nu = 17$ approximately. Following Schwarzschild and Williamson and Duff, one arrives at the equation,

$$\log \frac{LR^{20}}{M^{19}} = \log X + \log (1-X-Y) + 17 \log \mu - 123.1390 + \log \left[Q\, \Theta^{17} \frac{p_f}{t_f\, \theta_f^{1.5}} \left(\frac{x_f}{\xi_f} \right)^3 \int_0^{\xi_f} \theta_{1.5}^{20}\, \xi^2\, d\, \xi \right] \qquad (4)$$

The square bracket in the above equation is completely specified by the model defined by α. For energy generation by the proton—proton reaction only, $\nu = 4$, and using the equation for L given by L. H. Aller[4], one obtains

$$\log \frac{LR^{7}}{M^{6}} = -29.7018 + 2 \log X + 4 \log \mu + \log \left[Q\, \Theta^{4} \frac{p_f}{t_f\, \theta_f^{1.5}} \left(\frac{x_f}{\xi_f} \right)^3 \int_0^{\xi_0} \theta_{1.5}^{7}\, \xi^2\, d\, \xi \right]. \qquad (5)$$

Equations (3), and depending on the mode of energy generation assumed, either (4) or (5) give two equations among the five variables, L, M, R, X and Y.

In most recent work, the procedure has been to choose certain values of L, M, and R, (e.g., for the sun) and solve the equations for X and Y. Since the aim here was to construct a theoretical Hertzsprung—Russell diagram, it was decided that a better plan would be to choose sets of M, X, and Y, and solve for L and R. The procedure which was used to solve the equations is as follows:

(1) Choose a value of M. Then choose a set of X, Y, and C_o, and solve the equations for L and R. Then one can get ρ_c and T_c, the central density and temperature.

(2) Use tables of ρ/ρ_c and T/T_c, obtained from the integrations for each model to obtain the march of ρ and T through the star.

(3) Use a table of guillotine factors to obtain the march of $\log \tau$ through the star. P. M. Morse[5] has calculated one such table using quantum mechanics which gives $\log \tau$ for values of $\log \rho$ and $\log T$. Morse's table of guillotine factors has been used throughout this paper.

(4) Plot log τ against log ρ $(1 + X)$ to obtain an "observed" guillotine factor curve and compare this curve with the straight line of slope α which is postulated by the model.

(5) Adjust C_o until the best agreement is obtained between the "observed" curve and the straight line of slope α.

This procedure gives for each set of M, X, and Y, values of L and R as well as ρ_c and T_c. As X and Y are varied with M kept constant, a region is traced out in the log L—log R plane where theoretical stars should be found.

Carbon Cycle Models. It was first assumed that the carbon cycle was the only source of energy. The procedure above was employed to solve equations (3) and (4). The regions in the log L—log R plane for constant mass are shown in figure 1 as grids with lines of constant $X + Y$ and X. The lines of positive slope are lines of constant $X + Y$, the other lines are lines of constant X. The curved boundary on the left represents the line for which $Y = 0.00$ and X takes on various values. No point to the left of this line can denote positive values of Y. Such areas were outlined for a series of masses from log $M = -0.70$ to log $M = 0.00$ and also for various values of α. These regions have the striking feature that they are practically identical for different masses and values of α, apart from the positions in the log L—log R plane. In other words as M and α change, the grid receives a translation in the log L—log R plane but does not receive an appreciable change in shape or orientation. Therefore interpolations between different masses and between different values of α (for which integrations have been performed) is relatively easy and safe.

As has been pointed out by Williamson and Duff, and others, the representation of the guillotine factor is of extreme importance. It was felt that an overall representation of the guillotine factor curve was more justified than a closer fit for either the central region or the outer region of the star. The type of fit considered best is shown in figure 2 in which representative guillotine factor curves are reproduced. A study of a great many such curves obtained for various masses and values of α shows that the best model (value of α) changes as the mass changes according to Table I on the next page.

The final grid-like regions shown in figure 1 are for the values of α shown in the table above. They have been obtained by interpo-

TABLE I

log M	a
−0.70	0.43
−0.60	0.41
−0.40	0.37
−0.25	0.34
0.00	0.25
0.20	0.20

lating between the values of α, 0.25, 0.375, and 0.500, for which integrations are available.

It would be desirable now to see how the regions outlined in figure 1 compare with actually determined values of L, M, and R of stars. To do this, an interpolation must be made between the areas shown in figure 1 for the mass of the star concerned. This can be done readily. As an example, suppose a star has a mass

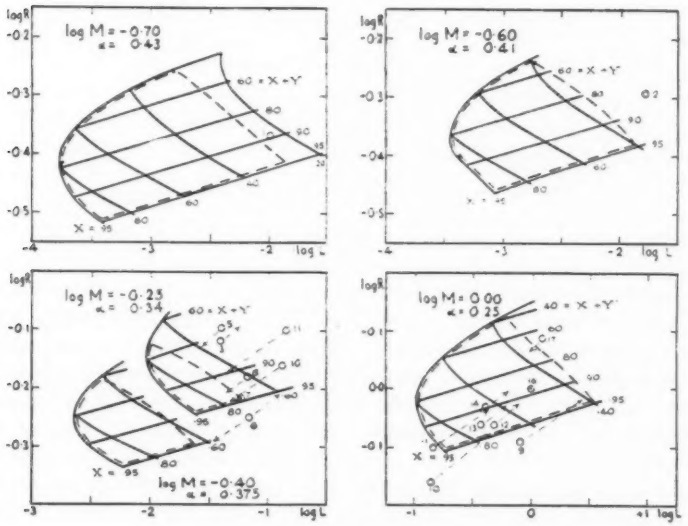

FIG. 1

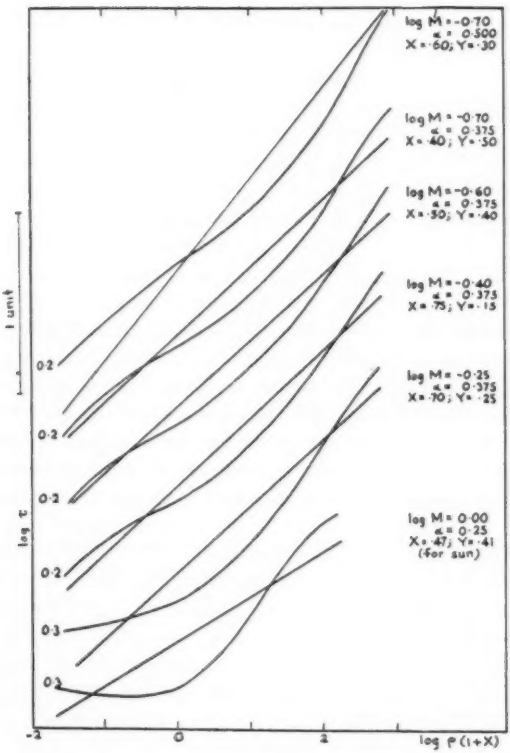

FIG. 2

corresponding to log $M = -0.10$. Then the area for log $M = 0.00$ is shifted toward the area for log $M = -0.25$ just enough to compensate for the change of 0.10 in log M. Or, vice versa, the star's plotted position is shifted in the opposite direction by the same amount. The log R and log L scales must then be shifted or disregarded. This procedure is employed in figure 1. The stars listed in Table II have been plotted as open circles, using the values of log L, log M, and log R given by G. P. Kuiper[6]. The serial numbers are used for reference. The arrows indicate where the stars would appear in the outlined areas. It is to be noted that

TABLE II

No.	Star		log M	log L	log R	Type*	Sp.	M_b	Remarks
1	o_2Erid	C	−0.70	−1.96	−0.37	V.B.	M5e	9.5	
2	Kr. 60	A	−0.60	−1.77	−0.29	V.B.	M4	9.0	
3	−8° 4352	$\overline{AB}$	−0.45	−1.40	−0.12	V.B.	M4	8.1	
4	ADS 3210		−0.44	−0.37	−0.13		G5	5.55	Hyades Star
5	μ Her	$\overline{BC}$	−0.35	−1.37	−0.10	V.B.	M4	8.0	
6	η Cas	B	−0.33	−1.16	−0.25	V.B.	K5	7.52	
7	Castor	C_2	−0.247	−1.24	−0.22	S.B.	K6	7.73	
8	Castor	C_1	−0.201	−1.16	−0.18	S.B.	K6	7.53	
9	η Cass	A	−0.14	−0.09	−0.09	V.B.	G0	4.84	
10	70 Oph	B	−0.13	−0.86	−0.16	V.B.	K4	6.78	
11	ξ Boo	B	−0.12	−0.83	−0.10	V.B.	K5	6.70	
12	ξ Boo	A	−0.06	−0.32	−0.06	V.B.	G8	5.42	
13	α Cen	B	−0.06	−0.43	−0.06	V.B.	K1	5.70	
14	70 Oph	A	−0.05	−0.38	−0.03	V.B.	K1	5.56	
15	ζ Her	A	−0.02	0.59	0.29	V.B.	G1	3.15	No solution
16	Sun		0.00	0.00	0.00		G2	4.62	
17	α Cen	A	0.04	0.10	0.09	V.B.	G4	4.37	

*Type: Visual binary (V.B.); Spectroscopic binary (S.B.)

star No. 15, ζ Her A, has not been plotted; it does not fit at all into the scheme being described. The other sixteen stars all give possible solutions and not one falls in the excluded region to the left of the curved boundary in figure 1. Star No. 4 of the Hyades cluster indicates a very low hydrogen content as do all the Hyades stars. It should be pointed out that the two stars No. 3 and No. 5 plotted in the third diagram of figure 1 belong to the region for log $M = -0.40$ and not to the region for log $M = -0.25$. These two stars are interesting because they indicate that $X + Y$ is only 0.4, that is, 60 per cent. of the mass of the star is heavy material. Although such a composition is not forbidden, it is very different from any other star's composition. It may be significant that these two stars are the only two of the list in which the components of the binary system are unresolved, and where the two components have been treated as identical.

For the stars plotted, the "observed" guillotine factor curve never deviates from the straight line postulated by the model by more than a factor of two except in the case of the Hyades star

where a straight line approximation is rather poor. This fit of the guillotine factor curve to the postulated straight line is an indication of the adequacy of the models in so far as the opacity is concerned.

Since we now have a theoretical diagram in terms of log L—log M—log R space, it is desirable to convert it to a more conventional Hertzsprung—Russell diagram in terms of the absolute

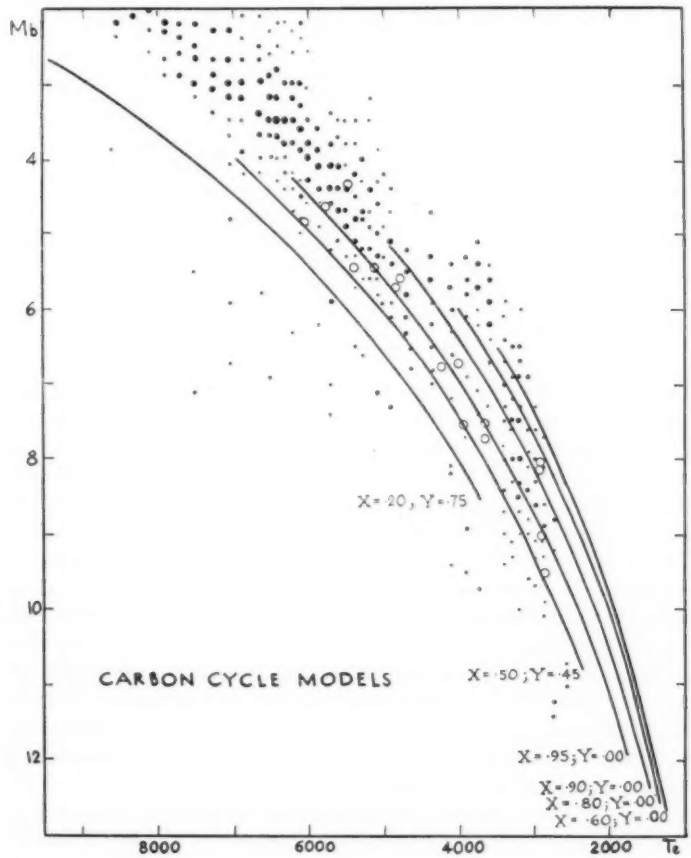

FIG. 3

bolometric magnitude M_b and the effective temperature T_e. The observational diagram has been taken from a paper by K. O. Wright[7], converting to the above scales by using the empirical bolometric corrections and temperature scale of Kuiper[8]. Wright's diagram is shown in figure 3, the size of each dot being roughly proportional to the number of observed stars represented by it. The stars of known L, M, and R, given in Table II, are plotted as open circles. The lines in the diagram are lines of constant chemical composition and are determined from the data shown in figure 1. The upper terminations of the lines shown correspond to log $M = 0.0$; the lower terminations correspond to log $M = -0.7$ except for the three lines on the right which have been cut off. The three lines on the left show how the lines vary if $X + Y$ is kept constant and X changes. The three lines on the right indicate how the lines change as $X + Y$ is decreased. The line $X = 0.60$, $Y = 0.00$ represents roughly a definite limit beyond which stars should not be found if they obey the proposed carbon cycle models. This limit corresponds to the envelope formed by the upper sides of the regions shown in figure 1 (near $X = 0.60$, $Y = 0.00$).

Proton—Proton Reaction Models. It has been suggested by L. H. Aller[5] and R. E. Marshak[9] that the proton—proton reaction may be an important source of energy in red dwarfs. Now that there are models available which apply directly to stars of all masses less than that of the sun, it seems advisable to investigate further the possibility of the proton—proton reaction in red dwarfs.

The first difficulty which arises is the violation of the assumption the energy is generated in the core only; 40 per cent. of the energy is generated outside of it. This is probably not too serious since if the radius of the core were 1.5 times as great, then nearly all of the energy would be included. It is unlikely that this effect will cause much change in the equilibrium of the radiative envelope, but the numerical values obtained below should be considered with this in mind.

The procedure used previously for the carbon cycle was repeated in exactly the same way using equations (3) and (5). The first big difference found is in the form of the log L—log R grid for constant mass. Instead of an extended area as in figure 1, one now gets only a very narrow band. This means that a star of given mass must fall very near to a fixed line in the log L—log R plane in order that a

reasonable solution for X and Y may be obtained. Such bands were obtained for various values of M and α. The guillotine factor curves were studied and from them the best value of α was determined for each mass. The curves themselves are much like those obtained for the carbon cycle models and the overall fits of the curves to the postulated straight line are slightly better than the fits for the carbon cycle. Having interpolated as before to obtain models corresponding to the best values of α for each mass, the diagram in figure 4 was constructed for $X + Y = 0.90$. The

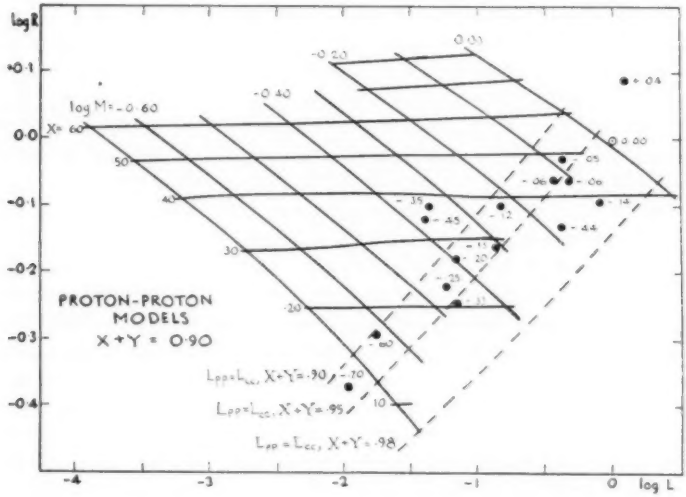

FIG. 4

horizontal lines are lines of constant X, the other lines are lines of constant mass. As $X + Y$ is varied, the lines of constant X shift parallel to themselves while the lines of constant mass, because of the property mentioned above, remain nearly fixed.

A test of the possible existence of the proton—proton reaction in stars is to see to what extent the stars of known L, M, and R conform to the diagram in figure 4 insofar as the mass lines are concerned. The stars of Table II are plotted in figure 4 with the corresponding values of log M indicated. Many of the points do

not fall near the lines of correct mass. If it is assumed that log L and log R can be in error by 0.1, then five of the stars give no solution whatever. Even if log L and log R are allowed to be in error by 0.15, three stars still give no solution. Among these three are Castor C_1 and Castor C_2 for which L, M, and R are known quite

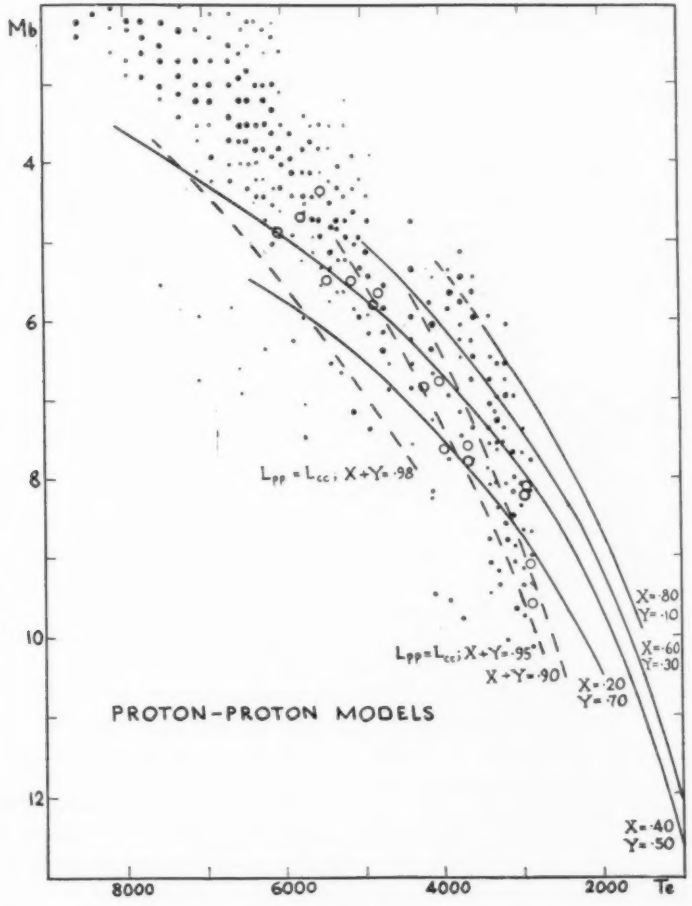

FIG. 5

accurately. The sun does conform to the proton-proton reaction scheme.

This diagram was now converted to the conventional Hertzsprung—Russell diagram (figure 5). Again the full lines are lines of constant chemical composition. This diagram does not fit the observations quite as well as the diagram from the carbon cycle models. It would appear that the lines shown should be steeper to fit the observed diagram best.

Comparison of the Two Energy Processes. If it is assumed that both the carbon cycle and the proton—proton reaction are possible, then the temperature of the central portion of the star will be important in determining which reaction is dominant. This is due to the large difference in the two values of ν for the two reactions. Using recent data given by Aller[5], it is found that the ratio of the energy production by the carbon cycle to energy production by the proton—proton reaction is given by the equation

$$\frac{E_{cc}}{E_{pp}} = 6.6\,\frac{1-X-Y}{X}\left(\frac{T}{15\times 10^{6}}\right)^{13} \tag{6}$$

where the subscripts cc and pp refer to the carbon cycle and the proton—proton reaction respectively. This equation can be integrated graphically to obtain L_{cc}/L_{pp} for a series of central temperatures. This was done and lines corresponding to $L_{pp} = L_{cc}$ were obtained for $X + Y = 0.90$, 0.95, and 0.98. These lines are shown as broken lines in figure 4. Because of the high power to which the temperature enters, the lines separate definitely the area in which the proton—proton reaction is dominant (to the left of the lines) from the area in which the carbon cycle is the main source of energy (to the right of the lines). Similar lines obtained from the carbon cycle models agree very well with those shown.

From figure 4 it is seen that only two stars of known L, M, and R can derive their energy by the proton—proton reaction if $X + Y$ is only 0.90. As $X + Y$ increases, more and more stars are included in this group, and at $X + Y = 0.98$ all of the stars should derive their energy from the proton—proton reaction. The proton—proton reaction models in general predict central temperatures which indicate that the carbon cycle should be used provided $X + Y$ is not too large.

When the lines corresponding to $L_{pp} = L_{cc}$ are found using the carbon cycle models, and are plotted in the diagrams of figure 1,

it is found that all of the stars of Table II fall either on the carbon cycle side of the lines or very near to them. (In the case of three stars a change in log R of 0.07 will put them on the carbon cycle side of the line.) Not one of the stars is decisively on the proton—proton reaction side of the lines $L_{pp} = L_{cc}$. The carbon cycle models are therefore fairly consistent for all of the stars of Table II.

The lines $L_{pp} = L_{cc}$ are also shown plotted as broken lines in figure 5. The proton—proton reaction is dominant to the right of the lines shown. For $X + Y = 0.97$, nearly all of the stars in the lower part of the main sequence should derive their energy from the proton—proton reaction. As $X + Y$ is decreased, more and more of the stars should derive their energy from the carbon cycle. The stars below the main sequence are almost certainly carbon cycle stars. There are other stars on the right edge of the diagram which may be proton—proton reaction stars. To decide which energy generation process is acting in any star is impossible unless $X + Y$ is known fairly well.

It is of particular interest that it is possible to obtain a solution for X and Y for the sun on the basis of the proton—proton reaction. From figure 4 it is seen that a small shift in α from 0.25 must be made to put the mass line for log $M = 0.00$ through the sun's plotted position. It is also seen that $X + Y$ should be at least 0.96 in order that the carbon cycle may be ineffective. For $X + Y = 0.98$, the proton—proton reaction model gives for the sun, $X = 0.74$, $Y = 0.24$, $\rho_c = 124$ gms. per c.c., $T_c = 16 \times 10^6$ °K.

Conclusions. Two different modes of energy generation have been considered in conjunction with a number of "straight line" models. Assuming that an overall fit of the guillotine factor to the postulated straight line is best, it has been shown that the opacity is never in error by more than a factor of two through the part of the star in which log $\rho > -2$. It is found that the degeneracy may be as high as 20 per cent. in the central parts of the star. The electrostatic correction to the pressure and the radiation pressure are found to be very small. It should be remembered that about 40 per cent. of the energy is generated outside of the core if the proton—proton reaction is operating. The assumption of constant chemical composition is probably as good as can be made at this time.

The source of energy in red dwarfs is of great importance and it would be desirable to be able to say if the proton—proton reaction

is actually possible, and if so, what the source of energy is in any red dwarf. While this investigation does not give a conclusive answer it does indicate certain facts which may be helpful.

(1) A comparison of the M_b—T_e diagrams shows that the carbon cycle models predict a main sequence which fits the observed diagram better than the main sequence predicted by the proton—proton reaction. The carbon cycle also predicts a sharp edge on the upper side of the main sequence which is at least suggested by observations.

(2) The carbon cycle gives a solution for X and Y for all of the stars of Table II with the exception of No. 15. A solution can be found for the Hyades stars if X is made small. The proton—proton reaction gives a solution for only about two-thirds of these stars but does give a solution for X and Y for the sun in good agreement with spectroscopic evidence.

(3) If both reactions are allowed, it is found that the carbon cycle models predict values of $X + Y$ for the stars of known L, M, and R such that the carbon cycle is the chief source of energy in all of them. The proton—proton reaction models, because they do not fix $X + Y$ definitely, leave the source of energy as predicted by the central temperatures undetermined.

These above points favour slightly the carbon cycle as the source of energy in red dwarfs. Probably the greatest needs for the dermination of the source of energy in red dwarfs are a better knowledge of L, M, and R for specific stars, and a comprehensive study of the very coolest and faintest red dwarfs.

The author wishes to express his gratitude to Professor R. E. Williamson for suggesting this problem, and giving many valuable suggestions. He is indebted to the National Research Council of Canada, for the financial assistance which made this study possible.

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Number 25

THE VARIABLE SPECTRUM OF THE STAR H.D. 218393*

By Ian Halliday

Introduction

FOR some time the star H.D. 218393† has been known to possess a most unusual spectrum. It has therefore received considerable attention. It is an emission-line star of early type, having been classified variously as B-type and early A-type. Descriptions of the spectrum have been given by Merrill,[1,2] by Harper,[3] by Swings and Struve,[4] and by Struve.[5]

The spectrum has strong hydrogen absorption lines with emission present at Hα, Hβ, Hγ, and sometimes Hδ. The character of these lines undergoes extensive changes, sometimes showing double absorption lines, and often double emission at Hβ. The H and K lines of Ca II are generally very strong, and the spectrum also contains strong helium lines. At times a rather large group of metallic absorption lines, mostly Fe II, Ti II, Cr II, Mg II, Si II, is very prominent, resembling such lines in the spectrum of α Cygni. These lines will be referred to as the α Cygni lines. At other times these lines become very weak and then only a very few of them can be seen. Perhaps it is this great variation in the appearance and disappearance of the α Cygni lines that has made a careful study of this spectrum so desirable.

The earliest work on the spectrum of H.D. 218393 consisted of general descriptions of the spectrum with particular reference to the peculiarities. Radial-velocity measures for some of the more prominent lines were given. An extensive analysis by Struve[5] described the results of observations from 51 plates taken at the McDonald Observatory during the summer of 1943. A velocity

*Summary of a thesis submitted in partial fulfilment of the requirements for the M.A. degree at the University of Toronto, 1950.

†R.A. $23^h\ 2^m.6$; Dec. $+49°\ 40'$ (1900); ptm. mag. 6.85.

curve for the higher members of the Balmer series of hydrogen lines was plotted and a correspondence with the intensities and velocities of the α Cygni lines was noted. Struve gave reasons for believing this star to be a rapidly rotating star surrounded by a large atmosphere consisting of two or possibly more shells. He suggested that many of the phenomena may be due to a type of prominence activity, which would appear to be much more powerful than any which is observed on the sun.

Most of the plates used for the present study were taken with the one-prism spectrograph of the David Dunlap Observatory fitted with the 25-inch camera lens, which gives a dispersion of about 33 A./mm. at Hγ. The plates show the region of the spectrum from about λ3900 to λ4900. Three fairly continuous series of plates of two or three months' duration were obtained during 1946, 1947, and 1949, with a few plates only taken in 1948. In addition, several plates taken at the Dominion Astrophysical Observatory, Victoria, were lent to the author by Dr. Beals of the Dominion Observatory, Ottawa. Four of these were of the visual region showing the strong emission line at Hα, while the others were of the photographic region.

Features of the Spectrum

Hydrogen Lines. The hydrogen lines are always prominent in the spectrum and show emission components resembling the emission in P Cygni. At Hα and Hβ there is usually emission present both on the red and violet sides of the absorption component, while at Hγ and Hδ the emission is confined to the red side. A study of the emission at Hβ on the David Dunlap Observatory plates showed that the emission components vary in relative intensity. As a rule, the red component is stronger than the violet one, which sometimes disappears almost completely. Another peculiar feature of this spectrum is the doubling of the hydrogen absorption lines which is observed on roughly 15 per cent. of the plates. An additional absorption component appears on the violet side of the usual absorption line, the displacement corresponding to a velocity of about 150 km. per sec. The additional line is weaker than the undisplaced line and may last for two or three days.

Other observers of this star have noticed similar variations in hydrogen emission and absorption. The phenomena seem to be

entirely sporadic and no dependence on other features of the spectrum could be found. In particular, both variations seem independent of the radial velocities of the hydrogen absorption lines. As Struve suggested for the star AX Monocerotis,[6] the doubling of the absorption lines could be caused by a sudden tremendous outburst from a very low level in the atmosphere.

Helium Lines. The helium lines provide the evidence that this is a very rapidly rotating star. They originate at the lowest levels in the atmosphere where the rotation is most rapid, and as a result, they are extremely broad and shallow lines. The two most prominent lines are those at λ4471 and λ4026. The latter one, however, was usually too faint for good observation on the Dunlap plates, due to under-exposure in this region. Accurate radial-velocity measurements of these lines are very difficult because of the great width of the lines and the absence of a strong absorption core. The measures made, however, agree with earlier results in which a large negative velocity was observed for the helium lines. The average velocity for λ4471 on 72 Dunlap plates was −74 km. per sec. This represents a negative shift of about 60 km. per sec. in excess of that observed for any other lines, with the exception of the secondary hydrogen absorption lines previously mentioned.

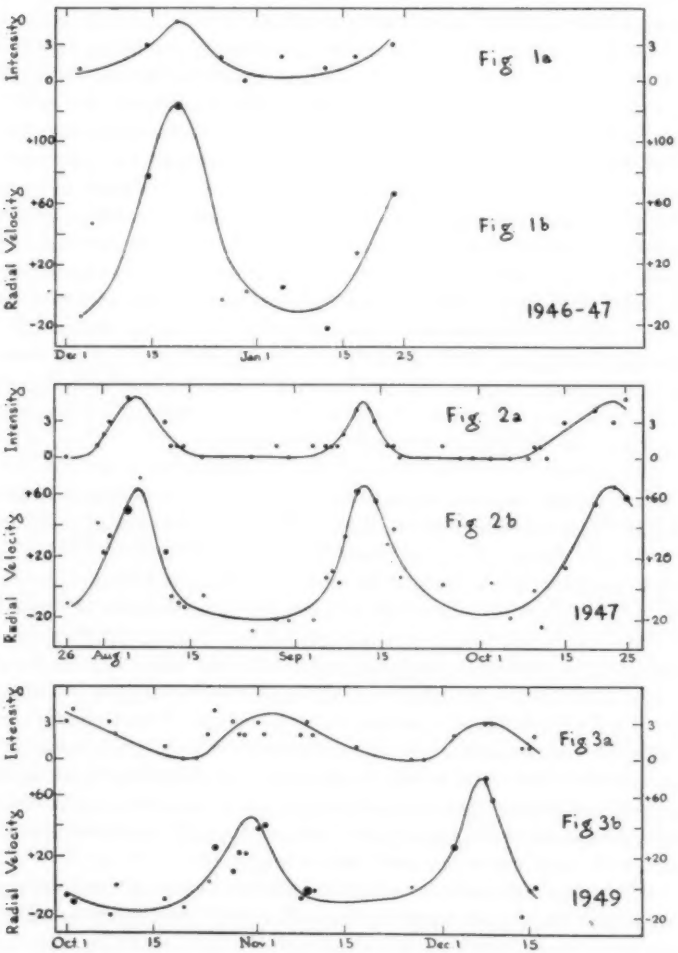
On several plates the line at λ4471 appears as a double line. The additional line was identified as a line of Ti II at λ4468 which usually is not resolved from the helium line. Similarly a Ti II line at λ4025 must often be blended with the helium line at λ4026. While this blending of metal lines with the helium lines may at times affect the measured helium velocities it cannot be the primary cause of the violet shift which persists even when almost all the metal lines are absent from the spectrum.

α Cygni Lines. In order to study the variations in the intensity of the αCygni lines, eye estimates were made. The intensity on each plate was denoted by an integer from 0 to 5 inclusive, consideration being given both to the number and the intensity of the lines present. A rating of 0 was given to a plate with an almost complete absence of the α Cygni lines, and a rating of 5 to one where the lines were very numerous and very strong.

When the ratings were assigned and the values plotted, it was found that they conformed quite well to a smooth curve. This showed a sharp rise to maximum activity and a similar decline,

about two-thirds of the curve consisting of the shallow minima between the maxima. Figures 1a, 2a, 3a show the three curves thus obtained for the series of plates in 1946, 1947, and 1949.

A period of roughly 35 to 40 days is indicated from the curves.



An attempt was made to determine a more exact period which would fit all observations from 1946 to 1949. While a period of 37.5 days seemed to fit best, none could be found which would be in good agreement with all observations.

Radial-Velocity Measures

Much information about the physical conditions in the atmosphere can be obtained from a study of radial-velocity measures. When a reasonably continuous series of observations has been made, such a study is of particular value because it is then possible to draw radial-velocity curves.

The radial velocities of all lines on 85 of the Dunlap plates were measured. These plates comprised the three series mentioned above, together with four plates taken from August to October, 1946. A large proportion of the lines measured were extremely faint which meant considerable difficulty in identifying the lines. Each of 70 different lines was identified on two or more plates. Of these, 63 were lines of singly-ionized metals, mostly Fe II and Ti II.

Hydrogen Velocities. In his paper Struve[5] plotted a radial-velocity curve from measures of the higher members of the Balmer series. This curve showed a continuous variation in the velocity within the limits +40 km. per sec. and −60 km. per sec., with a suggestion of a period of about 36 days over a single cycle. In a recent paper[7] Merrill showed that a continuous variation in velocity exists from member to member in the Balmer series. On different plates the progression may be either to higher or lower velocities as one proceeds to higher members of the series. The Dunlap plates are not suitable for studies of this type since they show only the lower members of the series. Radial-velocity measures of these lines are less likely to give reliable values than the higher members available to Struve and Merrill, largely because of the emission components.

Calcium Velocities. The calcium H and K lines are strong, but unfortunately they appear weak on the Dunlap plates due to underexposure in this region. The measures are, therefore, subject to large uncertainties and the scatter is large. The interstellar components are not strong but have been detected by Merrill,[7] who obtained an average value of −10.2 km. per sec. when they appeared resolved from the stellar components, and −12.9 km. per

sec. when they were not resolved. A plot of the values given by Struve shows a curve similar to, and in phase with, his plot of the hydrogen velocities. The range, however, is smaller, namely from +15 km. per sec. to −20 km. per sec. The Dunlap measures did not show a well-defined curve; the average value from 93 line-measures was −14 km. per sec.

α Cygni Velocities. The number of metallic α Cygni lines measured on any one plate ranged from 0 to 53. The measures of all metal lines except the calcium H and K lines were averaged. The reason for excluding the H and K lines is that while the average for the other metal lines ranges from about +120 km. per sec. to −20 km. per sec., the calcium lines are nearly always confined within the range 0 to −20 km. per sec. This may mean that the calcium lines originate at a different atmospheric level from the other metal lines due to the low ionization potential for calcium.

The average for all plates on which two or more α Cygni lines were measured are listed in the table, which also lists the measured hydrogen and helium velocities. The successive columns give the Julian date, the velocity of Hγ, Hδ, He I 4471, the number of α Cygni lines averaged, and their average velocity. For three days on each of which several plates were taken in a matter of hours, the values from the last two columns have been combined as shown in footnotes of the table.

When these average values for the α Cygni lines were plotted for the three series of observations, they were found to define good curves. (See figures 1b, 2b, 3b.) The size of each circle represents, roughly, the number of lines averaged to give its value.

These velocity curves were then compared with the α Cygni intensity curves, which had been drawn quite independently. Immediately it was obvious that a definite correlation exists. To show this the appropriate intensity curve has been drawn just above the corresponding velocity curve.

A preliminary examination confirms what was first noted by Merrill, namely, that the radial velocities have large positive values when the lines are most intense. The two curves seem to be entirely in phase. The scatter of the radial-velocity measurements is, naturally, greatest at times of minimum α Cygni activity when the lines are both weak and few in number.

The possibility that the observed radial-velocity curve was due

J.D. 2,430,000 +	Hγ	Hδ	λ4471	α Cygni Lines		J.D. 2,430,000 +	Hγ	Hδ	λ4471	α Cygni Lines	
				No.	Aver. Vel.					No.	Aver. Vel.
2,053.825	−11	−17	− 43	29	+ 69.9	2,468.638	−18	−26	−105	4	− 00.8
079.719	−06	−13	−131	..	..	469.629	−23	−14	−120	4	− 36.5
082.729	−13	−23	− 44	6	+ 18.6	470.650	−17	−12	− 92	..	..
113.685	−01	−03	− 91	3	+ 01.8	473.664	−21	−16	− 51	7	+ 13.1
157.597	−29	−34	−103	4	− 14.8	478.641	−26	+02	+ 20	14	+ 55.9
168.514	−07	−38	− 81	20	+ 79.3	481.757	+17	+23	..	6	+ 67.1
173.659	−12	+52	− 46	40	+123.5	483.674	−14	−09	− 38	26	+ 59.5
181.447	−36	+12	− 84	3	− 03.3	3.190.642	−18	−21	− 33	14	− 05.9
185.469	+06	−13	− 92	7	+ 03.0	191.681	−15	−14	−141	28	− 10.2
190.510	−12	−16	− 87	11	+ 06.6	197.673	−26	−10	− 97	7	− 18.3
198.484	−14	−03	− 57	13	+ 22.5	198.647	−22	−13	− 75	9	+ 02.4
203.488	−02	−16	− 24	12	+ 27.8	206.612	−05	+01	−105	7	− 07.8
208.519	+04	+19	− 65	21	+ 66.0	209.629	−37	−40	−115	3	− 14.5
392.812	−18	−06	− 29	2	− 11.3	210.574	−46	−70	−105	..	..
397.853	−04	+03	− 46	8	+ 42.6	213.615	−33	−27	− 31	4	+ 04.2
398.874	−11	−03	+ 11	19	+ 22.9	214.603	−21	−21	− 82	28	+ 25.7
399.843	−09	−10	+ 01	22	+ 33.2	217.581	−37	−33	−114	22	+ 09.8
402.740	−03	+10	+ 23	53	+ 49.7	218.634	−26	−16	− 69	18	+ 22.9
*404.813	..	−09	..	4	+ 72.7	219.626	−25	−07	− 33	13	+ 22.6
408.772	−12	−18	− 59	17	+ 23.1	221.603	−22	+07	−109	17	+ 38.3
409.825	−12	−11	− 61	12	− 06.5	222.581	−10	−07	− 59	27	+ 40.4
410.848	−08	−21	− 66	14	− 10.7	228.593	−17	−24	− 26	23	− 07.4
411.818	−08	−13	+ 03	10	− 13.0	229.553	−18	−06	−111	17	+ 03.0
414.792	−16	−17	−137	8	− 05.2	.561	−15	−23	− 82	19	− 08.1
422.710	−08	−15	− 68	3	− 28.4	.569	−15	−24	− 72	16	− 02.6
426.903	−20	−19	− 94	7	− 20.1	.639	−21	−28	−107	15	− 02.7
428.718	−07	−34	−125	4	− 20.6	.691	−14	−27	− 99	12	− 00.9
432.694	−17	−20	− 07	5	− 21.0	.701	−26	−25	− 84	18	− 05.2
434.783	−14	−07	− 22	5	+ 07.2	230.551	−18	−18	− 66	19	− 02.2
435.738	−10	+09	− 11	5	+ 11.4	237.623	−16	−30	− 60	2	+ 14.0
436.840	00	+24	..	4	+ 04.0	.704	−16	−26	− 49	3	+ 09.5
437.822	−02	−36	..	6	+ 34.8	246.619	−22	−21	− 97	2	+ 00.4
439.819	−05	−06	− 87	24	+ 62.9	248.643	−23	−15	..	..	..
442.893	+05	−07	− 76	9	+ 57.0	253.493	−12	−12	− 35	12	+ 15.5
444.812	+04	+18	− 50	2	+ 28.4	.576	−12	−04	− 72	14	+ 21.4
445.747	+01	+11	− 49	6	+ 38.0	.624	−11	−07	−100	15	+ 31.4
446.840	−17	+10	− 31	2	+ 07.1	.645	−09	+02	− 49	13	+ 39.9
453.671	−38	−29	− 99	7	+ 02.5	258.553	+13	+23	− 77	20	+ 71.3
456.686	−63	−51	− 76	..	..	259.666	−11	+07	−127	20	+ 57.8
458.718	−57	−41	− 88	..	..	264.594	−05	+14	− 59	8	− 20.0
461.660	−31	−27	− 64	4	+ 04.1	265.589	−09	−07	− 98	9	− 01.7
464.642	−36	−28	− 03	2	− 19.8	266.550	−24	−19	− 89	12	+ 00.9
467.683	−52	−23	..	..	..						

*Spectrum accidentally cut off above λ4300.

Average of 97 metal line-measures on 6 plates on J.D. 2,433,229 = − 02.9 km. per sec.

Average of 5 metal line-measures on 2 plates on J.D. 2,433,237 = +11.3 km. per sec.

Average of 54 metal line-measures on 4 plates on J.D. 2,433,253 = +27.3 km. per sec.

to a type of selection effect was investigated and ruled out. It was found that the velocities of those metal lines which are nearly always present in the spectrum agreed very well at all times with the velocities obtained by including the weaker lines in the average values.

If the radial-velocity measures published by Struve for the α Cygni lines are plotted, a curve similar to the ones shown is obtained. It is in phase with both the hydrogen velocity and calcium velocity curves previously mentioned.

The radial-velocity curves have more sharply defined maxima than the intensity curves. For this reason it is easier to get a value for the period from the velocity curves. The estimates for the four periods available, including the measures made by Struve, ranged from 37 to 40 days with an average of 38.8 days. As before, no single period could be found which would fit all observations from 1943 to 1949.

Interpretations of the Observations

The physical interpretation of the intensity and radial-velocity curves for H.D. 218393 is difficult. The radial-velocity curve resembles that for a spectroscopic binary of large eccentricity, but the absence of a true period together with the observed changes in amplitude of the curve make a simple binary theory hard to support. Moreover, a binary theory does not account for the changes in line intensities of the metal lines or the radically different velocities of the hydrogen and helium lines.

An alternative explanation would be to interpret the radial-velocity curve as a pulsation of one shell of the atmosphere. The constancy of amplitude and period required for a binary orbit is not so critical for a pulsation theory, while the hydrogen, helium, and perhaps the calcium lines may be expected to originate largely at other atmospheric levels. The periodic peaks of the velocity curve would each correspond to a relatively rapid collapse of the shell, with the shallow bottom of the curve indicating a slow expansion back to the original expanded condition. The opposing forces involved would be gravity and radiation pressure. The observed acceleration from the curve seldom exceeds 25 cm. per second per second. If one assumes a mass of 2 $\odot$ and a radius of 6 $\odot$ for a star of this spectral type, this would be the acceleration

of gravity at about 8 or 9 radii from the centre of the star. An integration of the velocity curve about a mean axis indicates a total amplitude for the pulsation of roughly 8 times the assumed radius.

While some such pulsation theory may fit the velocity curve, it fails to account for the variations in intensity of the α Cygni lines. Maximum intensity of these lines is observed at times of maximum velocity of recession, and minimum intensity at times of maximum velocity of approach. Yet the physical conditions of temperature, pressure, and radiation field would be expected to be entirely comparable at these times.

Another interpretation of the curve would be to regard the bottom of the velocity curve as representative of the "normal" conditions in the atmosphere. The observed strengthening of the lines would then correspond to a periodic streaming of material from the shell towards the star. The outbursts which cause the doubling of the hydrogen absorption lines could be the mechanism for feeding this shell. One is reminded of solar observations where it is difficult to account for the amount of material which appears to be falling back towards the sun.

Further observations will be needed to obtain a complete understanding of the spectrum of H.D. 218393. The David Dunlap Observatory plans more observations, including the determination of a light curve with a photometer.

The author wishes to express his sincere thanks to Dr. C. S. Beals of the Dominion Observatory, Ottawa, for the use of the Victoria plates and for valuable discussion, and to Dr. J. F. Heard of the David Dunlap Observatory for his many helpful suggestions, for his general supervision of the work, and for the use of his extensive series of spectrograms made during the years 1946 to 1949.

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REVIEW OF PUBLICATIONS

A Concise History of Astronomy; by Peter Doig. Pages xi plus 320; 5½ by 8½ inches. Chapman and Hall, London, England. Price 21s.

Those who are interested in the history of astronomy have long felt the need of an up-to-date historical account, something to take the place of, let us say, Berry's *History of Astronomy* which was published in 1898 and has been out of print for many years. It is to fill this need that Peter Doig, Editor of the British Astronomical Association Journal and well-known writer on astronomical subjects, has written the book under review. And, all things considered, he has done it very well.

Mr. Doig had apparently set himself certain limitations. The *History* was to be short enough not to discourage the casual reader, it was to be simple enough to be understandable to one not well read in astronomy; at the same time it was to be sufficiently complete to serve the serious student as a reference book. Clearly these limitations have made for difficult compromises.

The *Concise History* is nothing if not concise, and this is especially true of the chapters dealing with earlier times. The ancients, for example, are dismissed in 40 pages. The scholar may be shocked by this brevity, but, in fact, there are few ideas of the ancient astronomers which pointed the way to further development of the science. Most of the ideas were dead-end byways; there is clearly no space in a concise work to explore these, interesting though they be. The same is not quite true of the great period of development from Copernicus to Newton, during which the facts of the motions within the solar system were discovered and the mechanism interpreted. This part of the history receives again about 40 pages, and it is here that this reviewer felt the only real disappointment in the book, for the treatment is not only too brief, but it is jerky and disconnected. A smoothing out of chapters 5, 6 and 7 with the addition of a few more paragraphs by way of evaluation would have been well worth the price of a few dozen more pages. This is a wonderfully interesting and satisfying period; it is a pity to gloss it over.

In pages 88 to 150 the author leads us through the periods of development of gravitational astronomy by the great mathematicians of the eighteenth century (a difficult development to describe without mathematical language), through the growth of the Greenwich and Paris Observatories, through the great individual discoveries of Halley and Bradley, through the life of the great Herschel (apparently much admired by the author for he gives Herschel an unexpectedly full treatment), through the early-nineteenth-century triumphs of the discovery of Neptune and the measurement of stellar distances, and the beginning of speculation on the nature of the galaxy and the nebulae. All this is treated in a concise but interesting way.

The rest of the history of astronomy from the middle of the nineteenth century to the present time comprises the second half of the book; and it is here that the author's earlier conciseness begins to pay dividends, for he has left himself space enough to do justice to the past hundred years. At this point, too, the character of the writing changes gradually from a man-by-man to a topic-by-topic treatment. The chapters become less a directory of astronomers with their contributions and more a survey of current astronomy with an historical flavour. Actually the latter half of the book is a good account of the present position of astronomy, and the reader who wants a popularly written survey of the subject without delving at all into technicalities could find few better treatments.

For the most part the author has resisted the temptation to retell the more interesting stories from the private lives of the astronomers; they make interesting reading, and, in a larger work, they have a value, but in a concise work they have no place. On the other hand the author has gone to some pains to include the birth and death dates of practically all the deceased astronomers that he mentions, and the dates of publication of the investigations of many of the living astronomers. Along with the index this fact in itself should make the book valuable for reference purposes. Unfortunately, though, the index is not complete as regards names (e.g. missing in the index from an eleven-page sample of text from p. 244 to 254 are more than a dozen names including such well-known names as Turner, Lyttleton, Brouwer, Wylie, Whipple, Swings). This is a great pity in a history book where the index is so important.

The author gives us more than a mere chronological tabulation of

discoveries. Occasionally he stops and gathers together a summary of the history of a particular topic, as for example on page 170 where he gives a table of the measures of the sun's distance from the time of Ptolemy to the present time, and on page 156 where he traces the increase of accuracy of measurement of a star's position from Hipparchus to the present time. By such means he successfully emphasizes the continuing progress of the science. In some other places his attitude is less satisfactory from the historical point of view. In dealing with topics which are at the present time in a very unsatisfactory state he sometimes fails to point this out, even gives a contrary impression. For example, the reviewer feels that he has erred in this way in dealing with stellar evolution on pages 286 and 287 in spite of his final qualifying paragraph on page 288.

Altogether *A Concise History of Astronomy* contains an amazing fund of information, accurate, and put together in an interesting manner. There have had to be omissions for the sake of brevity, and there have undoubtedly been inadvertent omissions as well. (For example, it is hard to defend the omission of S. A. Mitchell who devoted a lifetime to the collection of solar eclipse data.) Nevertheless, the book can be wholeheartedly recommended to anyone at all interested in astronomy or in the progress of man's knowledge of nature. It is a book to read and a book to keep.

J. F. H.

Kleine Raketenkünde: by Hans K. Kaiser. Pages 151; 5¾ × 8 inches. Mundus-Verlag, Stuttgart, Germany. Price 9 marks.

The literal translation of the title of this German book is A Little Information about Rockets. The author is the founder of a German society for space research and an authority on rocket development. The book is a popularly written, profusely illustrated historical account of rocket development from the earliest beginnings to the present time. Although the author is apparently intrigued by the prospect of interplanetary travel, he does not let himself be carried away by conjecture. He writes of facts.

The book opens with a short historical sketch of early rockets and their military use, which was far more extensive than one might think. Then follows a technical discussion of rocket principles, then a systematic account of the work of some modern pioneers in rocket

research: the American Goddard, the Germans Oberth, von Pirquet, Valier, Sangers and others. The author explains how German rocket research was taken over in the late thirties by the military authorities and how it culminated in the development at Peenemunde of the V1 and later the V2. A short account of the development of the jet aircraft is given and the dependence of this development upon earlier rocket research is stressed. A few pages are devoted to current rocket development, particularly the American experiments with the war surplus V2's. The book ends with a short account of proposals connected with space travel: the artificial satellite, for example. Appended are a short bibliography and a glossary.

Altogether *Kleine Raketenkünde* appears to be a sober, authoritative, semi-technical work which should have a place in the library of anyone who is seriously interested in rocket development.

J. F. H.

Pocket Encyclopedia of Atomic Energy, by Frank Gaynor. Pages 204, 5½ × 8¾ inches. New York, Philosophical Library, 1950. Price $7.50.

This book is a collection of definitions and explanations of about two thousand terms used in nuclear physics. They range from a six word definition of "scattering" to a twenty-one page isotope table. They include the abbreviations for nuclear reactions, such as BEPO, GLEEP and ZEEP. Force, foot-pound, speed, ammeter and kilowatt hour are defined, as well as mineralogical terms such as schroeckergerite and fergusonite. Almagordo, Atomgrad, Hiroshima and Oak Ridge (but not Chalk River) are amongst the geographical places listed. Short biographical notes of some of the workers in nuclear physics are given.

Nearly a quarter of the book is made up of tables, some of which would probably be conveniently accessible in the original form to most workers who might need them. There appears to be some redundancy in the data; under each element is listed the isotope, and their abundances, material already tabulated under each element in the isotope table. The author makes a great point of the inclusion of the equivalent German term under each term. For this feature to have been of optimum use, it seems that these might have been collected in a brief appendix, and arranged under the German term.

The author regards this as a tourist guide through the strange new land of the Atom. Most physicists who make their daily rounds in such a land do not need a guide of this type. The real stranger will need more information, as given in text-books. Whether there are enough tourists to make a book of this kind necessary is the publisher's problem. Yet as with any tourist guide book, this book is quite interesting for casual browsing.

It might be noted that if this is a pocket book, the purchaser needs a larger pocket, both to hold the book and the money it costs.

F. S. H.

OUT OF OLD BOOKS

By Helen Sawyer Hogg

Kirkwood's Gaps in Asteroid Orbits

From decade to decade, or century to century, the interest of astronomers swings around the heavens, concentrating for a while on certain objects, and then returning to them with the passage of years. So it has been with astronomical interest in the asteroids. During the first quarter of the twentieth century, when large numbers of uninteresting asteroids were found, astronomers were beginning to regard them largely as a nuisance—"vermin of the skies". The past decade or two however, has seen a considerable revival of interest in these objects for two reasons. First, the discovery of a number of remarkable asteroids such as Hermes and Icarus, which come well within the earth's orbit at perihelion, has shown us that there are sizable bodies in space which come closer to us than we had realized. And second, recent theories of the origin of the solar system from the original "solar nebula", and the formation of the asteroids by the collision of planet-sized bodies originally in the asteroid ring has turned speculative attention to these objects.

During the meeting of the American Astronomical Society this June, at the Kirkwood Observatory of the University of Indiana, a symposium was held on asteroids, honouring the fiftieth anniversary of the observatory and the work of Daniel Kirkwood (1814-1895), professor of mathematics at Indiana University some ninety years ago. His name is well known to most students of astronomy as the discoverer of "Kirkwood's gaps" in the asteroid ring.

Dr. Dirk Brouwer, Director of the Yale Observatory, who discussed Hirayama's families of asteroids at this symposium, commented that the discovery of the gaps in the asteroid ring by Kirkwood was quite parallel to the discovery of the solar apex by Sir William Herschel nearly a century earlier. In both cases, an astronomer with a brilliant hunch derived a most important result from a handful of observations. Herschel had so few stars, and Kirkwood so few asteroids, with which to work, that a statistician would not have put much faith in the result. And yet when, in the following decades, the available data was multiplied many fold, the results that each of these men had obtained were most beautifully confirmed. Kirkwood based his

first findings on only 87 asteroids—those whose orbits were then known. Nowadays the results from around 1500 asteroids confirm his discovery that in certain portions of the asteroid ring, at certain distances from the sun, there is a marked lack of asteroid material. These gaps are at distances where the periods of the asteroids are commensurable with the period of the great planet Jupiter, which would pull them out of their course when he came near them.

The first statement Kirkwood made of the asteroid gaps, apparently, and also of the gaps in the rings of Saturn, was before the Buffalo meeting of the American Association for the Advancement of Science, in August 1866. This particular meeting of the Association was "originally appointed to have been held at Nashville, Tenn." in 1861. - - - "In the mean time, the great rebellion breaking out, the meeting was not of course, called together, as that place was not either a fit or a safe one for loyal members to visit." (*Proceedings of the American Association for the Advancement of Science*, vol. 15, 1867). Kirkwood's comments on the asteroid gaps, with 87 known orbits, are published in this volume very briefly. These were expanded some months later in the statement of his hypothesis in *Monthly Notices*, vol. 29, page 96, 1868. Shapley and Howarth in their "Source Book of Astronomy" have already published a later paper by Kirkwood on this subject from the Annual Report of the Smithsonian Institution for 1876.

We reprint excerpts from the earlier paper in *Monthly Notices*, not including his lengthy table listing 97 individual asteroids with their distances, but publishing his conclusions from this tabulation. For the asteroids he mentions by name, we have inserted parenthetically their distances as taken from his table. The asteroid distances are all discussed in terms of the astronomical unit, distance sun to earth equals 1.

On the Nebular Hypothesis, and the Approximate Commensurability of the Planetary Periods. By Daniel Kirkwood, LL.D., Professor of Mathematics, Indiana University.

The views of Laplace in regard to the development of our planetary system have been confirmed in a remarkable manner by the recent progress of astronomical discovery. We have now (1868) 100 minor planets between *Mars* and *Jupiter*, of which 96 have been detected since 1845. The mean distance of *Flora*, the innermost member of the group, is 2.20; that of *Sylvia*, the most remote, 3.49. The breadth of the zone is, therefore, greater than the distance of the

Earth from the Sun; greater even than the entire interval between the orbits of *Mercury* and *Mars*. Moreover, the *perihelion* distance of *Sylvia* exceeds the *aphelion* distance of *Harmonia* by a quantity equal to the interval between the orbits of *Mars* and the Earth. - - - -

Why did not the Asteroid-zone form a single planet, and the rings of Saturn, one or more satellites?—In regard to the ring between *Mars* and *Jupiter* perhaps no satisfactory answer can yet be given. We may remark, however, (1) that being situated just within the orbit of *Jupiter*, the perturbations were greater than in any other part of the system; and (2), that, as the total mass of the asteroids is very small, the matter of the primitive annulus was extremely rare, so that the intersection of orbits, resulting from the perturbations, would be less likely to produce large planetary nuclei. - - -

As these parts of the solar system, viz. the rings of *Saturn* and the minor planets between *Mars* and *Jupiter*, appear to furnish strong arguments in favour of the nebular hypothesis, their phenomena may perhaps be further suggestive as to the *mode* of planetary formation.

The mean distance of a planet having—

A period equal to	1/2	that of Jupiter is	3.2776
"	4/9	"	3.0299
"	3/7	"	2.9574
"	2/5	"	2.8245
"	1/3	"	2.5012
"	2/7	"	2.2569

These distances all fall between the greatest and least mean distances of the asteroids. Now, do we find wider intervals in these portions of the ring than elsewhere? and if so, what is their physical cause? For the purpose of comparison we have, in the following table, arranged the minor planets in the order of their mean distances from the Sun. - - - - -

The mean between the distances of *Flora* [2.2014] and *Sylvia* [3.4927] is 2.8470; and as small bodies in the remoter part of the ring are more difficult of detection, the zone will be considered under two divisions. The inner section contains 72 of the 97 asteroids whose elements are known; the mean interval between them being 0.0081. The greatest gap in the order of distances occurs between *Ariadne* [2.2034] and *Feronia* [2.2654]. It is 0.0620, or nearly eight times the mean. This includes the distance at which seven periods of an asteroid would be equal to two of *Jupiter*. The chasm next in order of breadth is between *Thetis* [2.4737] and *Hestia* [2.5178]. This is 0.0441, or more than five times the mean. In the outer section the mean interval is 0.0286. The greatest hiatus is between *Undina* [3.1917] and *Freia* [3.3877]; the breadth being 0.1960, or more than eight times the mean. This includes the distance at which two periods of a planet would be equal to one of *Jupiter*. The second is between *Bellona* [2.7784] and *Terpsichore* [2.8563] (0.0779), and the third between *Leucothea* [3.0060] and *Aegle* [3.0549] (0.0489). The widest chasms in the zone of minor planets are thus found to include those distances at which the periodic times would be commensurable with that of *Jupiter*. These coincidences are not accidental. The *primitive* ring undoubtedly contained nebulous matter at these as

well as the intervening distances; and the present existence of such intervals may be accounted for as follows:—

A planetary particle at the distance 2.5—in the interval between *Thetis* and *Hestia*—would make precisely three revolutions while *Jupiter* completes one; coming always into conjunction with that planet in the same parts of its path. Consequently its orbit would become more and more eccentric until the particle would unite with others, either interior or exterior, thus forming the nucleus of an asteroid. Even should the disturbed body not come in contact with other matter, the action of *Jupiter* would ultimately change its mean distance, and thus destroy the commensurability of the periodic times. In either case the primitive orbit of the particle would be left destitute of matter. The same reasoning is, of course, applicable to other intervals.

MEETINGS OF THE SOCIETY

AT EDMONTON

November 10, 1949.—The meeting was called to order at 8:21 by the President. The minutes of the previous meeting were read and approved.

Dr. Gowan reported that arrangements were made for the Annual Dinner at the Corona, to be held at 6:30 on Dec. 8, 1949. A letter from Toronto was summarized by the chairman regarding the proposed change in the membership year. Fees would become due on Oct. 1 rather than Jan. 1. Mr. Blower moved and Mr. Stewart seconded that Toronto's proposals be approved. Carried. A Nomination Committee of Dr. Campbell, Mr. Blower and Mrs. Clark are to present a slate of officers at the December meeting. The Handbook talk was given by Dr. Campbell. Several items are of interest to the layman who likes to observe splendors of the sky. Mild weather and clear skies gave exceptionally splendid viewing conditions of Hunter's moon. The main speaker was Dr. Gowan who discussed "Solar Research" from two points of view. First comes the study of the solar radiation as it is received at the earth. Typical aspects are the total heat received, and the ultra-violet radiation which has important effects on plants and animals. The total heat is of interest for various reasons including weathering, and the possibility of sunshine contributing to house heating.

The second aspect of solar research is concerned with the nature of the sun as a typical star. The kinds of study are diverse and may be summarized as sun-spots, the surface temperature, the spectrum of the sun, the structure of the surface by the light from the corona, prominences, flares, and radio noise. Inferences about the real nature of the stars can be drawn from the information collected and analysed. There is plenty more to learn!

After a short discussion the meeting adjourned to Room 111 for refreshments. There were 33 members and visitors present.

December 8, 1949.—After dinner, the meeting was called to order at 8:05. The President, Mr. Stockwell, welcomed visitors and called for the minutes. These were read and approved. Dr. Campbell gave the Handbook talk and the observatory report. The improved control of clock, is a great convenience, and the thanks of the centre go to Prof. Harle, Mr. Phillips and Mr. Panar of the Electrical Engineering Department. Mr. Burt gave a summary of Skyward, the news sheets from Montreal Centre. Reports were adopted from the Treasurer, Secretary and Nominating Committee.

The main speaker was Prof. J. A. Harle, who took as his subject "The Engineer and Astronomy." The various aids to observation which have been developed through the ages were described and in many cases illustrated by slides. Highly skilled machinists and instrument makers can design and build small equipment. When the equipment is large enough so that bending under its own weight becomes important the experience and calculations of the engineer have to be called in. The control of large telescopes requires carefully

designed electrical apparatus. The partnership of the engineer and astronomer has been very fruitful and will continue so.

The meeting adjourned at 9:25 p.m. There were 55 members and visitors present.

January 12, 1950.—The President called the meeting to order at 8:21. The minutes of the previous meeting were read and approved. The thanks of the Society were offered to the last year's executive by the new President. An application for membership was received from Mr. R. O. Bird, 9911-99 St., and it was moved, seconded and carried that the application be approved. The Handbook talk was given by Dr. Campbell. He recommended as a useful pastime the finding in the sky, and watching over several evenings, the variable star Algol. He explained that Julian time using fractions of days is a great convenience to astronomers and gives the time correct to about 10 seconds.

The main paper of the evening was given by Dr. H. Jordan of the Mathematics Department on the subject "Orbital Motion". The main problem to be solved is that of predicting accurately where in the sky a planet or a planetoid will be a few months or a few years in the future. Simplification of calculations is possible because of the predominating mass of the sun and because of the great distances involved. This means that all perturbations (that is, effects of one planet on another) can be neglected as a first approximation. A chain of calculations can be worked out showing the approximate position of the planet in its ellipse. This is the two body problem and gives the Keplerian motion. The approximation can be improved by considering the ordinary elements of the orbits as functions of time, varying slowly. Hence the deviations from the simple ellipse can be obtained, and then improved, thus taking the perturbation effects into account. This is good enough for 100 years or so but tells nothing about the stability or about the ultimate fate of the solar system.

There is a new treatment of the three body problem restricted to two large and one very small mass, for example the sun, Jupiter and a planetoid. Even this is too complicated for mathematical treatment but some conclusions can be drawn. There are five points at which the small mass would not move and around these Poincaré proved an infinite number of closed orbits. Recently Sundman has worked out methods of treating problems of collision three at a time or two at a time.

The paper was followed by some questions and discussion during which the speaker was congratulated on a very clear presentation of the essentials of an extremely complicated subject. The meeting adjourned at 9:50 p.m. to Room A111 for the usual refreshments. There were 23 members and visitors present.

E. H. Gowan, *Honorary Secretary.*

The Royal Astronomical Society of Canada

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